9.2.2 Designing Low Alloy Steels

Let's Design a High-Strength Steel

Now let's replace carbon as the major "hardening" agent and **design** a high-strength low-alloy steel without much carbon in earnest. I'm going just through a few principles that illustrate the salient points I'm trying to make. For more information use this link.
We want to make relatively *cheap* steel that can be conventionally *welded* (liquid welding) but is quite "strong", i.e. hard and ductile. That means it must be low in carbon since we do not want martensite formation, which is bad for welding. For the same reason we do not want a lot of pearlite. If we think in terms of carbon steel the only choice left is relatively soft low-carbon steel.

We want, however, rather large hardness (plus a large number of other good properties) that we simply cannot get from a low-carbon steel. We do not want high-alloy steels either because they are simply too expensive, not to mention hard-to-weld. What we want to make is a "**high-strength low-alloy**" (***HSLA***) steel, one of the major "designer" steels in circulation today. This kind of steel has a market share of about 12 %, which is quite a lot - roughly 170 million tons per year. Its development was driven by oil and gas extraction (meaning, for example, steel for pipelines where welding is a must), construction, and transportation (meaning cars).
HSLA steels are also known as "**micro-alloyed steels**". This needs some explaining. When a steel person talks about "alloying", she is referring to elements *different* from carbon and the commonly accepted amounts of manganese, silicon, etc. Bearing this in mind, we now can distinguish *three* **alloy groups**:

- **Micro Alloy Steel**: Steel containing small amounts of vanadium, niobium and/or titanium and other stuff with usually less than 0.10 % individual concentration and and a total alloy element concentration of less than 0.15% on top of, e.g., manganese and carbon.
  The name is a bit unfortunate because "*micro*" obviously does not refer, as it should, to alloy concentration in the 10^{-6} or ppm or 0.0001 % range, but simply to a a concentration range considered to be "microscopic" in comparison to normal steel.
  Then we have the old two assignations:
- **Low Alloy Steel**: Steel containing less than 3.5% of alloying elements.
- **High Alloy Steel**: Steel containing more than 3.5% of alloying elements.

Our HSLA steel to be designed thus still contains the ubiquitous Manganese (up to 2%) and carbon - but not much. Around 0.07 % - 0.12 % carbon will suffice. The trick is that we do not use the carbon for producing cementite or martensite but for making **metal carbides**. Following the principles of hardening, as discussed in chapter 8, but *without* using martensite, you know now what you must do:

1. Use solid solution hardening. Use dissolved foreign atoms other than carbon that make it more difficult for dislocations to move.
2. Use precipitation hardening. Take care to keep the precipitates small (including some cementite that might still be formed). That means to worry about nucleation and temperature profiles.
3. Use grain size hardening. Keep the grain size small. That's not easy. Adding small amounts of alloy atoms that like to sit in grain boundaries (possibly in the form of small precipitates) and keep them from moving might do the job.
4. Use work hardening. Or maybe, don't. Work hardening means to deform your steel before you use it. It will get harder but also loose ductility.

For the *first* mechanisms we need to look at the relevant figure again. We also need to consider all the *affordable* elements *not* shown in this figure but here.

What we find is that atomically dissolved carbon and nitrogen have by far the biggest direct effect on the yield strength (owing to their being interstitials), and that phosphorous kept in solution is very good, too, (but, remember, very bad in cold weather.
Then we have silicon (Si), manganese (Mn) titanium (Ti) and copper (Cu, not shown in the figure) and some other elements as pretty good solution hardeners. Copper, however, has drawbacks (including its prize), and silicon causes problems here too. This leaves, in a first cursory evaluation, manganese (Mn), titanium (Ti), and to some extent nickel (N) and vanadium (V) as eligible alloying elements for solid solution hardening.

Manganese is the clear winner since it also neutralizes spurious sulfur (S) and is quite cheap.

Alloying Elements

Overview
Details
Science

The *second* mechanism calls for alloy elements that form precipitates either with the iron (of which there is plenty), with the little bit of carbon left, with iron *and* carbon, or with the few other elements around. But *not* with the manganese (Mn), please, because we need that dissolved as single atoms for hardness, and to round up and precipitate residual sulfur (S).
You also want your precipitates to have a melting point higher than iron to avoid hort shortness, and you want them to be hard so neither dislocations nor advancing microcracks can cut right through them.

  - Now look up manganese (Mn) in the periodic table. It sits right next to iron (Fe) and thus can be expected to be chemically similar. That makes you suspect that elements that like to form compounds with iron might also like to form compounds with manganese, which is not good. That rules out elements for micro alloying that like to form precipitates with iron.
    So what kind of precipitates should form? Carbides, of course. That also solves the other problems, because carbides typically have a very high melting point and are extremely hard. We now need alloy elements that are known to be strong "**carbide formers** ". That are all elements that form carbides (surprise!) *and* win against the iron in the competition for the carbon in there.
    All you have to do is to go through the periodic table, looking (experimentally) for good carbide formers. It's a feast for grad students once more. Many Ph.D. theses' and scientific papers will result.
    Elements like niobium (Nb), vanadium (V), titanium (Ti), chromium (Cr), zirconium, (Zr) or molybdenum (Mo), but also silicon (Si) or boron (B), emerge as possible contenders. All of them like to form very hard carbides with very high melting points. So we now go and try them out. Each one causes a hell of a lot more work than that little example I gave you with Copper (Cu) in aluminum (Al). What they do if several different ones are there at the same time will provide work for generations to come.

- We still have the *third* mechanism, keeping the grain size small.
  - That involves two major points:
    - Making small grains in the beginning (whatever and whenever).
    - Keep those grains from growing.

    If you look at the formation of a final ferrite structure from the liquid to the solid, the decisive grain sizes are the austenite grains at high temperature. To keep them from growing, you shouldn't give them much time to do so, i.e. you need to work on your cooling rate. In addition, with some luck, some of your alloying elements might like to produce their carbide precipitates in the grain boundary (easy nucleation) and this might help to keep the grain boundaries from moving. If it can't move, the grain can't grow.
    Of course, the iron-carbon phase diagram is not decisive for that any more. More work for grad students.

- I'm already discussing the processing or in other words the temperature profiling. This is crucial. Whatever you put into your HSLA steel to form carbides, it will only work if you cool down quickly. Otherwise all those carbides have time to grow into large sizes and you want them to remain very small, remember? Just one example: Niobium (Nb) or vanadium (V) works already at low concentrations around 0,1 % - provided you know what you are doing. Tiny niobium carbide particles of about 1 nm size (containing less than 100 alloy atoms) will increase the yield stress from about 20 MPa to 200 MPa, at a concentration of about 0.1 wt % Nb. "Huge" particles with diameters of 10 nm or larger have practically no effect anymore! Look at the simple Cu in Al example. It's all there except that the effects are more pronounced in the iron - niobium system.
  - The problem, of course, is that the outside always cools down faster than the inside. The "inside" thus stays "soft". All we can do is case hardening - only the "case", the outer layer is really hard. The word to introduce and recognize now is "**hardening depth** ". The question simply is: To what depth is the cooling rate fast enough to allow hardening? And how can we measure it? For the second question the answer is easy and given in this link.
    Whatever happens during quenching, major things only happen when the temperature goes below the transition temperature where austenite intends to change to ferrite. The formation of metal carbides, we might assume, also starts below that temperature. In plain carbon steel this "A_1" temperature is around 720 ^{o}C (1328 ^{o}F). If we could lower it, there wouldn't be so much time for carbide formation and the carbides stay smaller.
    Can we? Of course—by alloying the right element(s).

- Even if you overdid your "good stuff break", you should now have gotten the central message:

If you want to change the property of some material, alloy the *right* element(s) the *right* way.

- In normal human life, finding out what is right or wrong gives jobs to a lot of humans. And to lawyers. A hell of a lot of people working inside some religious organization are concerned about this topic, and they can tell you unambiguously if what you do is right or wrong with regard to what you eat, how you deal with your girl friend / spouse, how to raise your children, and so on. Then there is that parent-in-law who knows exactly what's right or wrong for her son or daughter, and so on. Just don't ask them about alloying elements.
  In contrast, as far as technical human life is concerned, the number of the scientists and engineers who know the right alloy elements from the wrong ones, and the right way to deal with them, is rather small.
  Which group has achieved more I leave open at that point.

- If you are into alloying, you should be aware of where you could succeed, and where not. The first law of applied science comes into its own. Using it, you will know that making big changes in **Young's modulus** by alloying just a little bit of something will not work - period! Or, to give another example, that alloying will *always* increase the electrical resistivity.
  Nevertheless, alloying plus proper processing does the trick in many cases. The fact that we have more than 1000 different steel alloys, with properties tailored to some particular needs, bears witness to that.